

The brown dwarf desert as a consequence of orbital migration

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ABSTRACT

We show that the dearth of brown dwarfs in short-period orbits around Solar-mass stars – the brown dwarf desert – can be understood as a consequence of inward migration within an evolving protoplanetary disc. Brown dwarf secondaries forming at the same time as the primary star have masses which are comparable to the initial mass of the protoplanetary disc. Subsequent disc evolution leads to inward migration, and destruction of the brown dwarf, via merger with the star. This is in contrast with massive planets, which avoid this fate by forming at a later epoch when the disc is close to being dispersed. Within this model, a brown dwarf desert arises because the mass at the hydrogen burning limit is coincidentally comparable to the initial disc mass for a Solar mass star. Brown dwarfs should be found in close binaries around very low mass stars, around other brown dwarfs, and around Solar-type stars during the earliest phases of star formation.

Key words: accretion, accretion discs — planetary systems: protoplanetary discs — binaries: close — stars: formation — stars: low-mass, brown dwarfs

1 INTRODUCTION

Recent surveys have demonstrated a high abundance of brown dwarfs in young clusters (Martín et al. 2000), star forming regions (Béjar et al. 2001), and the field (Kirkpatrick et al. 1999, 2000). Brown dwarfs are also reasonably common in wide binaries (Gizis et al. 2001). The sole well established exception is in close (semi-major axis $a \lesssim 4$ AU) binaries. The same radial velocity surveys that have been so successful in finding massive extrasolar planets show that brown dwarfs are rarely close binary companions to Solar-type stars (Marcy & Butler 2000; Halbwachs et al. 2000). This brown dwarf desert supports the conventional belief that massive planets and brown dwarfs form in distinctly different ways, and also suggests that some aspect of the formation or early evolution of brown dwarfs differs from that of stars.

One possibility for explaining the desert is to postulate that the formation mechanism for brown dwarfs is entirely different from that of *either* stars or giant planets. Reipurth & Clarke (2001), for example, suggest that brown dwarfs are objects whose growth towards stellar masses was curtailed by ejection from small multiple systems (see also Reipurth, Clarke & Delgado-Donate 2001). In their model, the desert arises because substellar objects that were *not* ejected continued to accrete, eventually reaching stellar masses.

In this paper, we investigate a less radical (and more limited) possibility. We show that the absence of brown

dwarfs in close binaries with Solar-type stars could be due to orbital migration within an evolving protoplanetary disc. This is the same process that is invoked to explain the presence of massive planets at small orbital radii (Lin, Bodenheimer & Richardson 1996), and which may also play a role in the orbital evolution of cataclysmic variables (Taam & Spruit 2001) and supermassive black hole binaries (Gould & Rix 2000). The critical assumption is that brown dwarfs form contemporaneously with the star, and thus become embedded within a young and relatively massive protoplanetary disc. Under these conditions, we show that migration efficiently clears out the desert by forcing the brown dwarfs into mergers with the star. This is in contrast to the evolution of massive planets, which have a chance of escaping the same fate by forming later, when the disc is close to being dispersed and cannot drive migration through to merger (Trilling, Lunine & Benz 2001; Armitage et al. 2001).

2 BROWN DWARF MIGRATION

We assume that close brown dwarfs companions form at essentially the same time as the star, either via fragmentation during cloud collapse, or via disc instabilities during the earliest protostellar stages (e.g. Bonnell & Bate 1994). The brown dwarf companions open up a gap in the protoplanetary disc, and their subsequent fate then depends upon the evolution of the coupled disc-brown dwarf system. If the

disc mass is large enough, relative to the brown dwarf mass, then the brown dwarf migrates in radius as the disc evolves as if it were a fluid element in the gas. This can be inward or outward, depending upon the sign of the radial velocity in the disc. If the disc mass is too low, on the other hand, the brown dwarf will act as a dam in the disc, holding up accretion and suffering minimal orbital migration (Syer & Clarke 1995). We show later that the first regime, where migration is rapid, is probably appropriate for brown dwarfs around Solar mass stars, while the no-migration outcome is likely if the star has very low mass.

2.1 Numerical methods

The interaction of a low mass secondary with particulate or gaseous discs has been extensively studied (Goldreich & Tremaine 1980; Lin & Papaloizou 1986). Based on this work, we model the interaction using a one dimensional treatment, in which we solve for the coupled evolution of the disk surface density $\Sigma(r, t)$ and brown dwarf semi-major axis a . The governing equation, including mass loss in a disc wind at a rate $\dot{\Sigma}_w(r)$, is (Lin & Papaloizou 1986; Trilling et al. 1998),

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[3r^{1/2} \frac{\partial}{\partial r} (\nu \Sigma r^{1/2}) - \frac{2\Lambda \Sigma r^{3/2}}{(GM_*)^{1/2}} \right] - \dot{\Sigma}_w. \quad (1)$$

where M_* is the stellar mass. The first term on the right-hand side describes the diffusive evolution of a disk in which the angular momentum transport can be parameterized via a kinematic viscosity ν . The second term describes how the disk responds to the torque from the secondary, which is approximated as a fixed function of radius $\Lambda(r, a)$. We adopt,

$$\begin{aligned} \Lambda &= -\frac{q^2 GM_*}{2r} \left(\frac{r}{\Delta_p} \right)^4 & r < a \\ \Lambda &= \frac{q^2 GM_*}{2r} \left(\frac{a}{\Delta_p} \right)^4 & r > a \end{aligned} \quad (2)$$

where $q = M_{\text{BD}}/M_*$ is the mass ratio of the binary, and Δ_p is given in terms of the disc scale height h by,

$$\Delta_p = \max(h, |r - a|). \quad (3)$$

The rate of migration of the brown dwarf is,

$$\frac{da}{dt} = - \left(\frac{a}{GM_*} \right)^{1/2} \left(\frac{4\pi}{M_{\text{BD}}} \right) \int_{r_{\text{in}}}^{r_{\text{out}}} r \Lambda \Sigma dr. \quad (4)$$

Tests show that the detailed form of the torque function is unimportant for determining the migration rate once a gap has been opened. We have used the same form adopted by Armitage et al. (2001) to study massive planet migration.

The use of equation (1) implicitly assumes that (a) the brown dwarf orbit remains circular, and (b) that there is no ongoing accretion across the gap. Current theoretical understanding does not permit a definitive answer to either question. Existing simulations suggest that the assumption of circular orbits ought to be reasonable for massive planets, and perhaps for low mass brown dwarfs, but that for more massive brown dwarfs ($M_{\text{BD}} \gtrsim 20M_{\text{Jupiter}}$) or stars the interaction with the disc may drive eccentricity growth (Artymowicz et al. 1991; Papaloizou, Nelson & Masset 2001). On-going accretion is likely to be substantially reduced at the

relatively large mass ratios appropriate to brown dwarf secondaries (Bryden et al. 1999), but the exact level is rather uncertain.

2.2 Disc model

For the disc, we use a variant of the Clarke, Gendrin & Sotomayor (2001) model, which combines viscous evolution with mass loss at large radii. The model is motivated by observations of disc photoevaporation in Orion (Johnstone, Hollenbach & Bally 1998), though the same process may also occur at a lower level for relatively isolated stars (Shu, Johnstone & Hollenbach 1993). Including mass loss from the disc enables the model to reproduce the observed rapid transition between accreting Classical T Tauri stars and non-accreting Weak-Lined systems (Clarke, Gendrin & Sotomayor 2001). We take,

$$\nu = 1.75 \times 10^{13} \left(\frac{r}{1 \text{ AU}} \right)^{3/2} \text{ cm}^2 \text{s}^{-1} \quad (5)$$

consistent with a $\Sigma \propto r^{-3/2}$ surface density profile. We start the runs with a steady-state surface density profile (accretion rate constant with radius), and assume $h = 0.05r$ at all radii.

Appropriate values for the mass loss are poorly known for the situation, relevant here, where the star is *not* part of a rich cluster such as Orion. We assume that mass is lost from the disc outside a critical radius $r_{\text{crit}} = 5 \text{ AU}$, with a radial scaling $\dot{\Sigma}_w \propto r^{-1}$. For most of our runs, we normalise $\dot{\Sigma}_w$ such that the total mass loss rate integrated to 25 AU is $5 \times 10^{-9} M_{\odot} \text{yr}^{-1}$. To gauge the sensitivity of the results to the mass loss prescription, we also run models with the mass loss rate reduced to $5 \times 10^{-10} M_{\odot} \text{yr}^{-1}$.

Figure 1 shows the evolution of the disc mass for initial masses of $0.1 M_{\odot}$ and $10^{-2} M_{\odot}$. We concentrate on the higher initial disc mass case, which is likely to be representative of the disc around a Solar mass star. A disc mass of the order of $\sim 0.1 M_{\odot}$ is comparable to the most massive discs inferred from mm wavelength observations (Osterloh & Beckwith 1995), and can also be justified theoretically – it corresponds to the marginally gravitationally unstable state expected as an endpoint of the disc formation process (e.g. Lin & Pringle 1990). For this model, a break in the evolution occurs at around 3 Myr, when the disc wind becomes dominant. The subsequent evolution is consistent both with the inferred time-dependence of the accretion rate for T Tauri stars (Hartmann et al. 1998), and with the evolution of the disc fraction with cluster age (Haisch, Lada & Lada 2001).

Operationally, we solve equation (1) using an explicit method on a non-uniform grid. The runs described below all used 300 mesh points, with an inner radius of 0.075 AU and an outer radius of 33.3 AU. At R_{in} a zero-torque boundary condition ($\Sigma = 0$) was used, while at R_{out} we set the radial velocity $v_r = 0$.

In our current implementation, brown dwarfs reaching the inner boundary at R_{in} are declared as mergers. We do not include any ‘stopping mechanism’, sometimes invoked to slow or halt migration of extrasolar planets at very small radii. This is because the evidence for such mechanisms is weak. Although there are plausible reasons why migration might stall at small radii – for example due to an inner magnetospheric cavity in the disc (Königl 1991) –

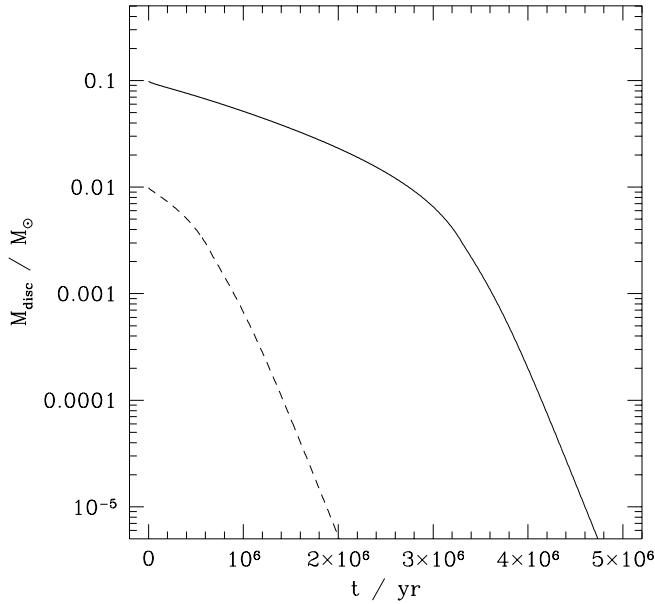


Figure 1. Evolution of the disc mass with time for the two disc models, which differ only in the assumed initial conditions. The solid line shows a model with an initial mass $M_{\text{init}} = 0.1 M_{\odot}$, and an accretion rate $\dot{M}_{\text{init}} = 3.3 \times 10^{-8} M_{\odot}/\text{yr}$. The dashed line is for a model with $M_{\text{init}} = 10^{-2} M_{\odot}$, and $\dot{M}_{\text{init}} = 3.3 \times 10^{-9} M_{\odot}/\text{yr}$. The disc is dispersed rapidly once the disc wind becomes significant.

the observed radial distribution of extrasolar planets can be matched satisfactorily *without* including any stopping mechanism (Trilling et al. 2001; Armitage et al. 2001).

2.3 Migration-driven mergers

Figure 2 shows the migration history of brown dwarfs embedded in protoplanetary discs with initial masses of $0.1 M_{\odot}$ and $10^{-2} M_{\odot}$. The brown dwarf mass was $0.04 M_{\odot}$, i.e. substantially less than the disc for the more massive initial disc model. Disc evolution in the initially more massive disc drives the brown dwarf into merger with the star for all initial orbital radii $a \lesssim 10$ AU. Migration is especially rapid for brown dwarfs with initial orbits inside ~ 2 AU. These objects are swept inside 0.1 AU within less than a Myr after the start of the calculation. Reducing the rate of mass loss from the outer disc by an order of magnitude tends to *increase* the extent of migration, as it means that there is a larger reservoir of gas exterior to the brown dwarf orbit at late times. For orbits with initial semi-major axis $a \lesssim 10$ AU, however, the change is relatively small.

As expected, this rapid migration does not occur if the disc mass is much smaller than the brown dwarf mass. For a disc with an initial mass of only $10^{-2} M_{\odot}$, the angular momentum reservoir of the brown dwarf is large enough to prevent substantial orbital evolution. Only a modest migration occurs before the disc wind disperses the disc and freezes the brown dwarf into its final orbit. The low mass runs provide a qualitative idea of the evolution around very low mass stars, where the initial disc mass is likely to be smaller than the mass of any brown dwarfs present. If we assume that the

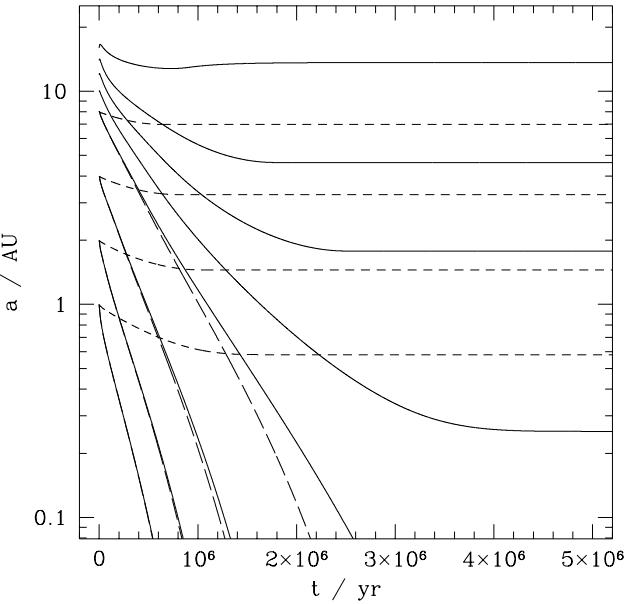


Figure 2. Orbital migration of a $0.04 M_{\odot}$ brown dwarf in a protoplanetary disc. The solid curves show how brown dwarfs with different initial orbital radii migrate in discs with an initial mass of $0.1 M_{\odot}$. All brown dwarfs with initial orbital radii $a < 10$ AU are swept inside 0.1 AU, and probably lost in mergers. We also show how some of the results depend on the disc model. Reducing the mass loss rate from the disc (long dashed curves) makes little difference to the migration history, while reducing the initial disc mass to $10^{-2} M_{\odot}$ (short dashed curves) almost halts inward migration.

initial disc mass is proportional to the stellar mass, then the results suggest that substantial migration would still occur for moderately less massive stars than the Sun, with masses $\approx 0.5 M_{\odot}$. For stars with masses of $0.1 - 0.2 M_{\odot}$, however, very little migration is expected.

Migration will efficiently empty the desert of brown dwarfs with initial semi-major axis $a \lesssim 8$ AU, provided that the initial disc mass is of the order of $0.1 M_{\odot}$. The only brown dwarfs that will remain at radii observable with radial velocity surveys are those that have migrated inwards from greater distances, before becoming stranded at small separations by the dispersal of the disc. Continuity demands that such objects must exist, but their numbers are generically likely to be small. In most models the disc gas is outflowing at large radii (Basu 1998; Hartmann et al. 1998) and tending to drive outward, rather than inward, migration. Moreover, as is evident from the divergence of the tracks in Fig. 2, migration leads a dilution in the number of brown dwarfs per unit logarithm in radius. Surveys have discovered some brown dwarfs at small radii – for example the outer companion (at ≈ 3 AU) of the HD 168443 system (Marcy et al. 2001) – so the observations require only a substantial rather than a complete depletion of the population. Quantitatively, Gizis et al. (2001) estimate that if brown dwarfs followed the same distribution of separations as stars, at least ten times the observed number would be expected with separations less than 3 AU. There is considerable uncertainty in this

estimate, but it nonetheless suggests that a theory for the desert needs to produce roughly an order of magnitude depletion in the population of short period brown dwarfs.

To estimate the range of initial orbital radii that will lead to surviving short-period brown dwarfs, we have run a series of models in which brown dwarfs were placed at larger initial radii in a $0.1 M_{\odot}$ disc. The results of these calculations are also shown in Fig. 2. For our disc model, binaries with initial orbital radii in the range $10 \text{ AU} \lesssim a \lesssim 14 \text{ AU}$ are progenitors of observable systems in which the final orbital radius is $a < 4 \text{ AU}$. Smaller initial separations lead to merger, as discussed already, while larger separations fail to migrate inwards into the observable window prior to disc dispersal.

To use these results to estimate the net depletion of the desert, we need to know the initial distribution of brown dwarf orbital radii. If we assume that the formation of binaries that include a brown dwarf is scale free (i.e. equal numbers per logarithmic interval of separation), then migration leads to a net depletion by an order of magnitude in the $0.1 \text{ AU} < a < 4 \text{ AU}$ range of orbital radii. Alternatively, we could assume that the initial radii of the binaries mirrored that observed for solar-type main sequence binaries generally. Duquennoy & Mayor (1991) parameterize the distribution with period P (in days) as,

$$f(\log P) \propto e^{-\left[\frac{(\log P - \bar{\log} P)^2}{2\sigma_{\log P}^2}\right]}, \quad (6)$$

where $\bar{\log} P = 4.8$ and $\sigma_{\log P} = 2.3$. This distribution is an increasing function over the range of initial radii of interest here, and thus we estimate a rather smaller depletion of brown dwarfs using this as the initial distribution. Between $0.1 \text{ AU} < a < 4 \text{ AU}$, we obtain a depletion by a factor of 6.

2.4 Rotation rates of merger remnants

The best observational test of this model would be the detection of a significantly larger brown dwarf frequency among close pre-main-sequence binaries, in which accretion is still ongoing. There may also be evidence for mergers within the distribution of stellar rotation rates. Unlike gas, which can be accreted via a magnetosphere with essentially zero net change in stellar specific angular momentum (Königl 1991; Armitage & Clarke 1996), a merging brown dwarf arrives with the Keplerian angular momentum near the stellar surface. The ratio of the brown dwarf to stellar angular momentum is,

$$\frac{L_{BD}}{L_*} = \frac{1}{k^2} \left(\frac{M_{BD}}{M_*} \right) \left(\frac{\Omega_K}{\Omega_*} \right) \quad (7)$$

where Ω_* is the stellar angular velocity, Ω_K the Keplerian angular velocity at the stellar surface, and $k^2 \approx 0.2$ is the radius of gyration for the star (assumed fully convective). For an initial rotation period $P \sim 7 \text{ dy}$, appropriate to many Classical T Tauri stars (Bouvier et al. 1993; but see also Stassun et al. 1999), $L_{BD}/L_* \gg 1$, so the merger leads to substantial spin-up. The results outlined above suggest that of the order of 10% of stars might have suffered such mergers with brown dwarfs. If the spin-down time-scale subsequent to merger is relatively long (of the order of a Myr), we would then expect a small fraction (a few percent) of Classical T Tauri stars to be rapid rotators as a consequence of mergers.

3 SUMMARY

We have shown that inward orbital migration of brown dwarfs, within an evolving protoplanetary disc, can account for a low frequency of brown dwarfs as close binary companions to stars with masses $M_* \sim M_{\odot}$. Migration depletes the initial frequency of brown dwarf companions at all radii where there is significant viscous evolution of the protoplanetary disc. This region could extend out to several tens of AU. Brown dwarfs with initially larger orbital radii $a \sim 10^2 \text{ AU}$ would be unaffected. In our specific model, migration leads to the destruction of all brown dwarfs with initial orbital radii $a \lesssim 10 \text{ AU}$, via mergers with the star which cause significant stellar spin-up. Orbits with $0.1 \text{ AU} < a < 4 \text{ AU}$ are partially replenished by brown dwarfs migrating inwards from still greater radii, but the net brown dwarf frequency at these radii is still reduced by a factor of 5-10.

The main prediction of the model is that brown dwarfs in close orbits ought to be up to an order of magnitude more common amongst the youngest pre-main-sequence stars (less than a Myr), as compared to the main sequence. For migration to occur, we also require that the initial disc mass be at least comparable to the mass of the brown dwarf. No brown dwarf desert is thus expected around the lowest mass hydrogen-burning stars ($0.1 - 0.2 M_{\odot}$), or indeed around other brown dwarfs, whose discs would have been too feeble to drive significant brown dwarf migration.

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